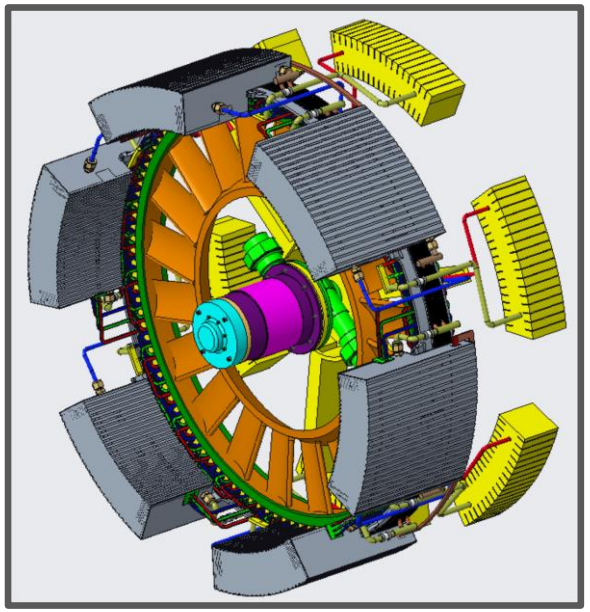
Electric Flightworthy Lightweight Integrated Thermally-Enhanced powertrain System (eFLITES)

Mr. John Yagielski, GE Research

ARPAe Project: 2238-1510
DE-AR0001353



8-fold increase in Power Density

- **Integrated Architecture**
  - Modular SiC inverters
  - Embedded direct-drive motor
- **High temperature**
  - Altitude-capable HV insulation
  - Power electronics
- **Embedded Cooling**
  - Direct-cooled motor armature
  - Inverters w/additively-manufactured cold-plate

Suite of transformational technologies to raise power density of GE's hybrid-electric systems to enable all-electric propulsion

eFLITES Project Overview

GE Aviation
NREL Transforming ENERGY

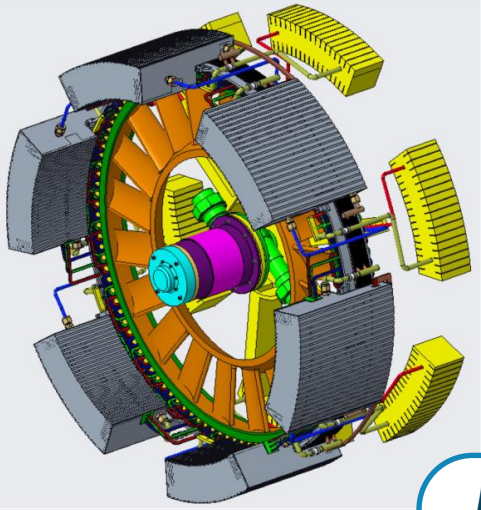
System Integration
- Mechanical Integration
- Performance Modeling
- Cost / reliability

sCO_2 pump

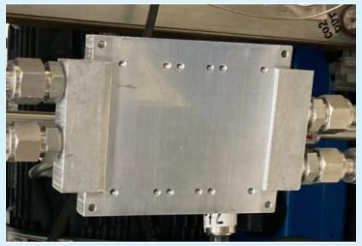
NREL Transforming ENERGY
GE Aviation
GE Research

sCO_2-based Thermal Management

HV-coil direct-cooled by sCO_2

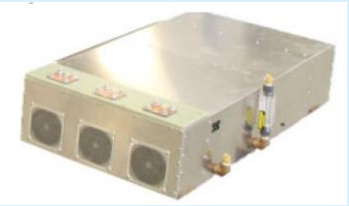


GE Research
GE Additive



Additively manufactured cold plate

GE Research
GE Aviation



MW-class VSC

Alternate: Current Source Inverter

GE Research

Modular dielectric-filled motor drive

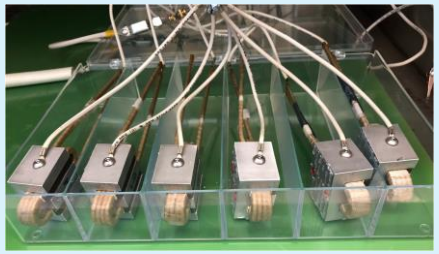
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
GE Research

High Temperature SiC module

GE Research
GE Gas Power
NREL Transforming ENERGY

High-Voltage Direct Cooled Winding

Ceramic composite insulation

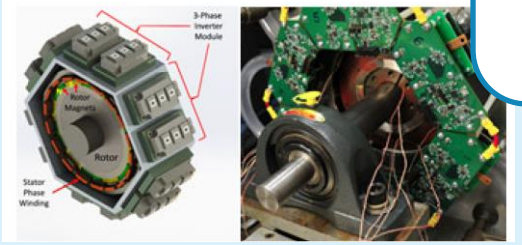


BACK-UP: Enhanced HV, altitude capable system

Direct-drive Motor Motor-Inverter Integration

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
GE Research

GE Aviation Systems
GE Research



SPM Machine & Integrated Inverter

- ❑ Suite of low TRL technologies to achieve goals
- ❑ Leveraging on-going developments
- ❑ Higher TRL back-ups included

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Motor Details

- **Direct-Drive**
  - No gear box weight & maximum propulsor integration
  - Form-factor enables integrated / distributed inverter
- **Inner-rotor, Halbach array surface PM motor**
  - Minimize rotor yoke iron weight
  - Air-cooled rotor via propulsor integration

Transformational Innovation

- **Direct-cooled HV / high temperature armature**
  - Segmented winding for maximum inverter integration w/tooth-wound coils to maximize fault tolerance
  - Hollow-conductor coils & core cooling jacket
  - Ceramic-based high-temperature insulation system

Key Technology Validation

- ✓ Coil forming & insulation processes developed
- ✓ Winding components characterized at altitude including voltage endurance at altitude & temperature
- ✓ Mechanical characterization & high-pressure tests
- ✓ Coils tested with sCO_2 at 2.7x current density*

(* vs direct oil-cooled)

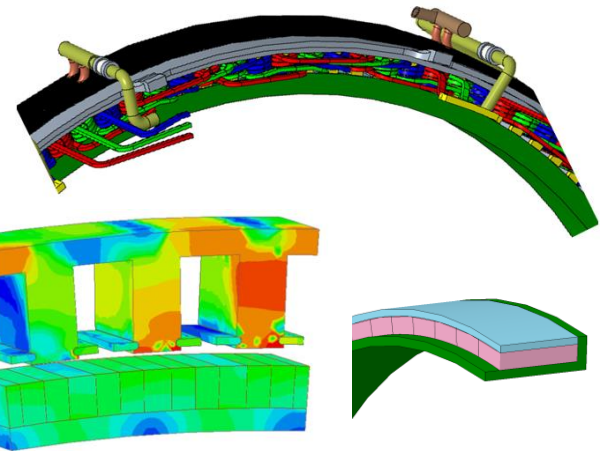
Ceramic composite insulation

High-pressure Direct-cooled coils

BACK-UP

Altitude-Proven HV Insulation

High-voltage / pressure isolators



Parameter	Value
Rotational Speed (rpm)	5,000
Mechanical Power Output (kW)	2,000
Voltage (V,l-l, rms)	820
Power Density (kW/kg)	>29
Efficiency @ cruise (%) (including TMS)	95

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Motor Drive Details

➢ Integrated - Modular Topology

- 6 @ 3-phase power blocks driving modular motor in fault-tolerant configuration
- GE 1.2kV Silicon Carbide (SiC) half-bridge modules
- Voltage-source baseline w/current-source alternate
- Reduced harmonics & EMI through optimized modulation

Transformational Innovation

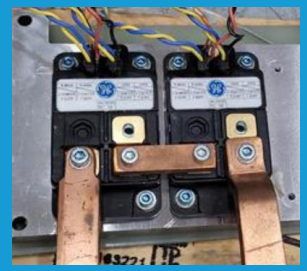
➢ Dielectric-filled power module w/embedded cooling

- GE SiC modules with custom substrate
- Additive cold-plate for high-pressure coolant
- High-temperature passive devices & integrated gate drive

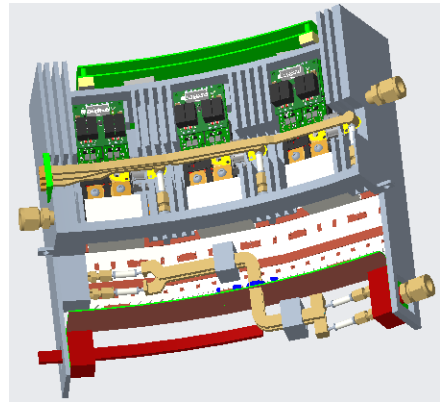
Key Technology Validation

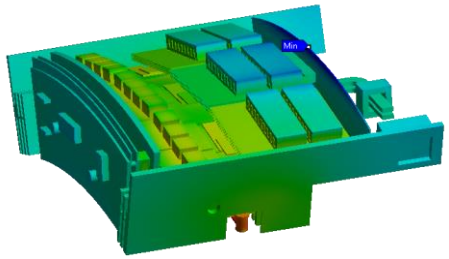
- ✓ Customized GE SiC module developed & manufactured
- ✓ SiC module characterized
- ✓ Additively-manufactured cold plates produced
- ✓ Cold plates over-pressure, leak tested & operated in sCO_2

Additively manufactured heat exchanger



High Temperature SiC module





Parameter	Value
System DC Bus Voltage	2,400
Power block rating (kVA)	410
Power Density (kW/kg)	>25
Efficiency @ cruise (%) (including TMS)	>99%

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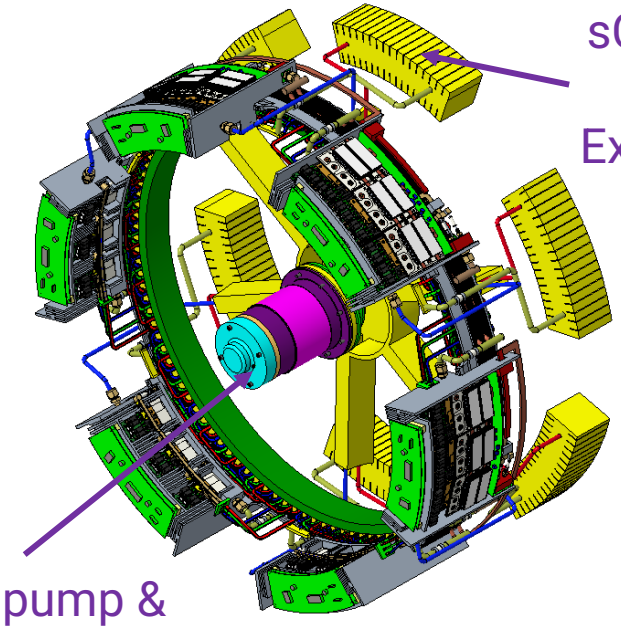
Thermal Management System Details

Transformational Innovation

- **Advanced sCO_2-based thermal "bus" for system cooling**
  - Superior combination of heat capacity w/low pumping power
  - Operating temperatures maximized for increased approach temperature to ambient → minimize heat exchanger weight & drag
  - Series connection of motor drive, stator core / DC-bus, then motor winding

- **Leveraging on-going thermal system development**
  - High-flow / high-temperature motor driven compressors
  - Test rigs for flow/thermal model calibration



Coolant pump & sCO_2 test rigs

Parameter	Value
Loss extraction (kW)	~140
Inverter thermal resistance (K/W)	< 0.005*
Motor stator thermal resistance (K/W)	< 0.003*

(* hotspot to ambient)

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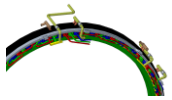
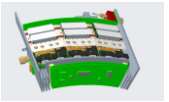
2MW @ 5000rpm / 2.4kVdc System Design – Tools & Trades

***Bold** are "vital few" to system-level optimization*

	Motor 	Motor Drive 	Thermal Management 
Analytical Tools	• 2&3D EM FEA for steady-state, transient, fault performance, & losses • 2&3D thermal FEA for steady-state performance • 2D mechanical FEA with test-derived properties	• Detailed circuit simulation for steady-state, transient performance & losses • 2&3D thermal FEA for steady-state performance • 3D mechanical FEA for pressures	• 1D thermal bus flow model • In-house, closed-form sCO_2 pump & motor sizing tools
Analyses & Trades	• **Multi-physics optimization of electrical and rotor mechanical performance** • Thermal / Electrical optimization of stator cooling & rotor magnet selection	• Drive performance & power quality • **Filter weight / performance optimization for power quality & component stress** • **EMI characterization** • **Control scheme confirmation** • Multi-physics optimization of cold-plate • Down-select of motor drive dielectric filler	• **Comprehensive system architecture down-select**

System

- **Detailed system-level 3D CAD for integrated design & assessment**
- **Propulsor-level system performance model for mission simulation**
- Component-level cost & reliability models

- ❑ **Suite of tools with proven prototype pedigree**
- ❑ **Analyses calibrated to previous & Phase 1 tests**
- ❑ **Fully leveraging GE Aviation hardware & system models**

Parameter	Value
Grav. Power Density (kW/kg)	>11
Vol. Power Density (kW/l)	>13
Cruise Efficiency (%)	>93%
TO & Climb Avg Efficiency (%)	>94%

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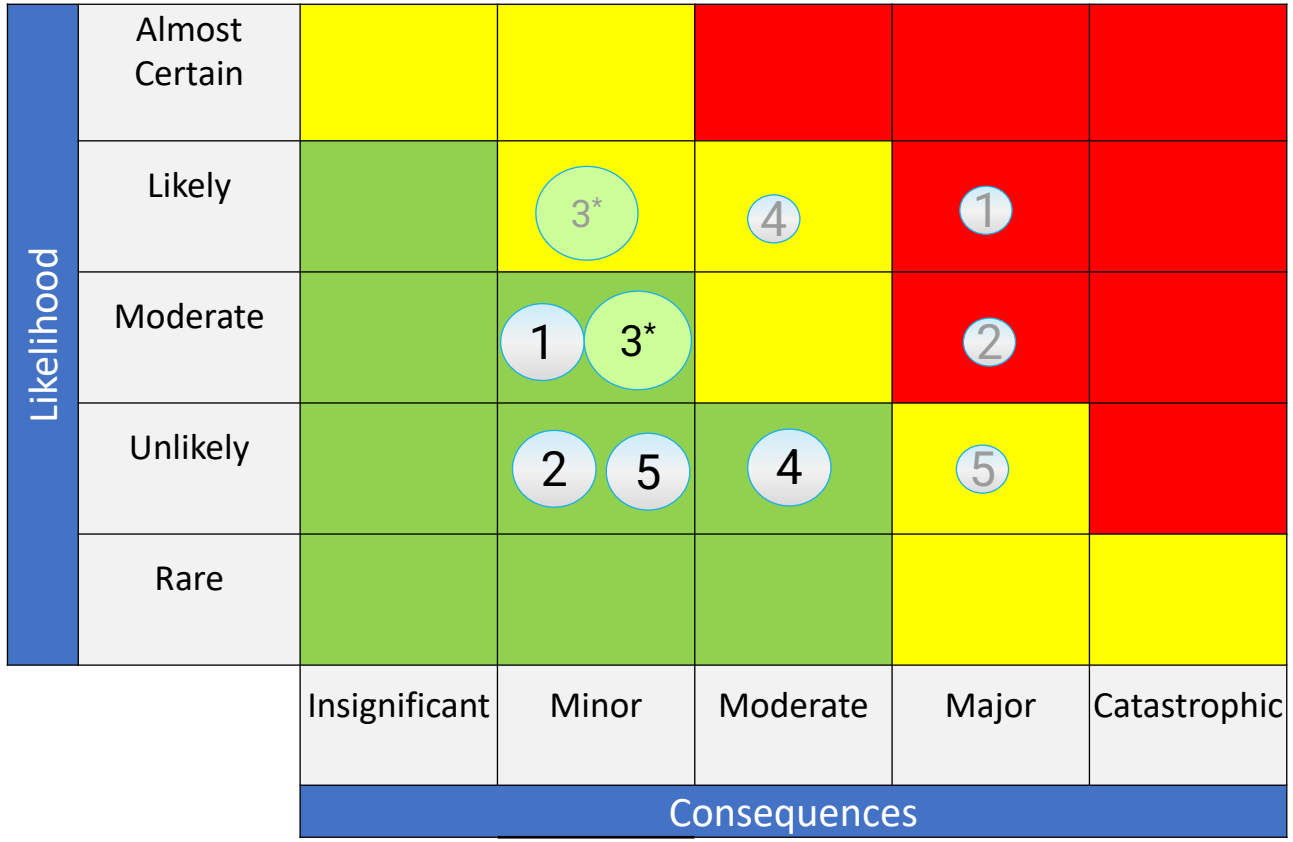
Updated Risk Assessment



Initial Risk Ranking	#
Inverter Power Module (VSI) w/high-temperature coolant	1
Direct-cooled armature ~2x current density & high temperature coolant	2
Reliable, Altitude-capable ceramic composite insulation	3*
Leak-free, altitude & HV capable motor/inverter electrical / hydraulic connections	4
Complete inverter/motor integration	5

* Initial ceramic composite insulation risk partly mitigated by backup system

- ✓ ***Successful proof-of-concept pathfinder hardware test campaign***
- ✓ ***2MW system concept design demonstrates feasibility***
- ❑ ***Demonstrator design & hardware testing in-process***

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Technology-to-Market Approach

➢ **Continue GE's Electric Aircraft Propulsion Development (10+ yrs.)**
- Build on legacy of commercial & military aircraft propulsion systems
- Enhanced by on-going & new government partnerships (NASA, FAA, DOE, **ARL**)
- Grow GE business supply chain (power electronics, HV electric machines, additive manufacturing, etc.)

➢ **Expand the teams' suite of Intellectual Property (IP)**
✓ **Three patent disclosure filed** (insulation and converter technologies)
- Materials, architecture, geometry and design of power dense electric machines and converters
- High-power aviation thermal management systems for electrical systems
- Enabling manufacturing techniques (including additive)

➢ **Envision parallel technology adoption paths**
- **Early demonstration & adoption for novel commercial & non-commercial aircraft**
- Operating benefits of all-electric for small & thin-haul aircraft w/energy storage technology improvements
- Fuel-burn reductions drive step-wise introduction into narrow-body commercial aircraft

➢ **Leverage cross-industry insight to identify & drive synergies with adjacent industries**
- National Renewable Energy Lab (NREL)
- University-of-Wisconsin – Madison
- GE Businesses (Gas Power, Renewables, etc.)

Looking Ahead – Phase 1 Completion & Phase 2 Start

***Bold** are "vital few" to de-risking*

Key Risks – Initial Assessment	Phase 1 – Round 1 Pathfinder Hardware	Phase 1 – Round 2 Concept Hardware	Phase 2 Pre-production Hardware
Inverter Power Module (VSI) w/high-temperature coolant	✓ SiC module build & characterization ✓ Cold plate production & proof tests	❑ **Demonstrator phase leg pump-back test**	❑ Converter full-power pump-back test
Reliable, Altitude-capable ceramic composite insulation	✓Electrical & Mechanical proof tests ✓Altitude & temperature voltage endurance	❑ **EPD-insulated coil module thermal proof test**	❑ **Statorette multi-factor HALT tests**
Direct-cooled armature ~2x current density & high temperature coolant	✓Proof-of-concept test		❑ sCO_2 rig upgrades & component tests at operational conditions
Leak-free, altitude & HV capable motor/inverter electrical / hydraulic connections	✓ Electrical proof tests	❑ **Coil module thermal proof test (back-up insulation)**	❑ Winding process qualification tests ❑ **HV isolator build and test**
Complete inverter/motor integration	✓ 2MW system concept design	❑ Demo system concept design	❑ Demo system detailed design ❑ **Device-level reliability assessment** ❑ **TMS hardware development & subsystem testing**
Current Source Inverter (Alternative)	✓ Architecture selected & concept design	❑ Low-power prototype test ❑ Direct-cooled inductor pathfinder build & test	❑ Design maturation & comparative performance assessment
Tech-to-Market – Barriers to Adoption	✓ Cost, Performance & Reliability models ✓ IP Asset summary & Prior Art ✓ Regulatory landscape & engagement	✓ Market & Landscape Analysis ❑ Freedom to Operate Assessment ❑ **Additional patent disclosures**	❑ **Finalize integrated system demonstration (post Phase 2)**

- ❑ **Key risks reduced at completion of phase 1**
- ❑ **Pre-production hardware design & test at outset of phase 2**
- ❑ **Execute process qualification & reliability testing in parallel with demo design, built & test**

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Q & A

https://arpa-e.energy.gov